UNIVERSITÀ DEGLI STUDI DI NAPOLI "FEDERICO II"
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE DII

MASTER THESIS IN MECHANICAL ENGINEERING FOR THE DESIGN AND PRODUCTION

DESIGN AND OPTIMIZATION OF LASER DRILLING PROCESS FOR THE PRODUCTION OF SHAPED HOLES ON AEROSPACE SUPERALLOY TBC COATED VIA STATISTICAL APPROACH

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CANDIDATE:
CARMINE DI VILIO
M64/703

Avio Aero
A GE Aviation Business

A LEADING AEROSPACE COMPANY





Previous thesis of this project

Iacobelli V, Necula C (2015) - Experimental study on fiber laser drilling of aerospace alloys: statistical approach and technological interpretation *(Università degli Studi Di Napoli "Federico II")*

Siviero D (2016) - Statistical approach in aerospace industry innovation. A case study: the shaped holes drilling process *(Università degli Studi Di Napoli "Federico II")*

Amato V, Panetta A (2017) - Experimental study for shaped holes manufacturing by fiber laser technology for aerospace applications *(Università degli Studi Di Napoli "Federico II" – Università degli Studi della Campania "Luigi Vanvitelli")*

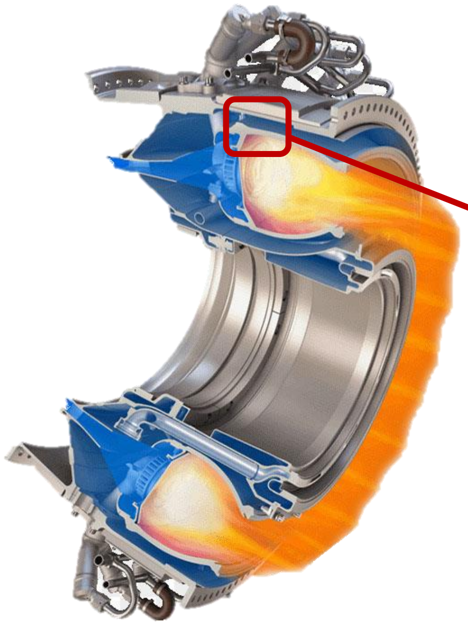
Di Napoli A, Tonin B (2018) - Experimental study for shaped holes manufacturing by fiber laser technology for aerospace superalloys: statistical approach and technological interpretation *(Università degli Studi della Campania "Luigi Vanvitelli" - Università degli Studi Di Napoli "Federico II")*

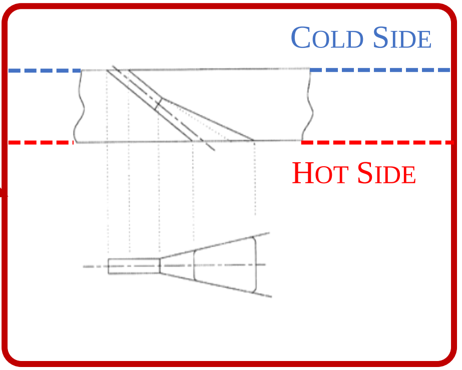
Ambrosio s, Bellotta I (2019) – Design and optimization of laser drilling process for the production of shaped holes on aerospace superalloys via statistical approach *(Università degli Studi Di Napoli "Federico II" – Università degli Studi della Campania "Luigi Vanvitelli")*

Tartaglione A, (2020) – Optimization and industrialization of laser drilling process for the production of shaped holes on aerospace superalloys via statistical approach *(Università degli Studi Di Napoli "Federico II")*

Since 2017 this project is part of a research contract with the name: «Analisi ed ottimizzazione del processo di foratura laser e controllo degli shaped holes con l'ausilio di metodi statistici avanzati»

IN SOME AEROSPACE APPLICATIONS, VARIABLE SECTION HOLES ARE USED, CALLED *SHAPED HOLES*, TO INCREASE THE COMBUSTION CHAMBER COOLING.

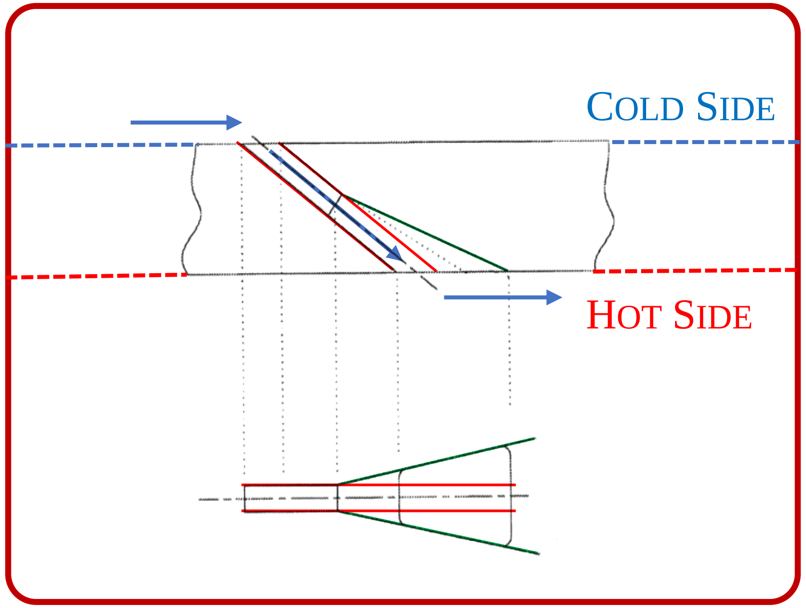




THESE ONES ARE COMPOSED OF TWO PARTS:

- METERING HOLE: IT REFERS TO THE CYLINDRICAL SECTION OF THE HOLE

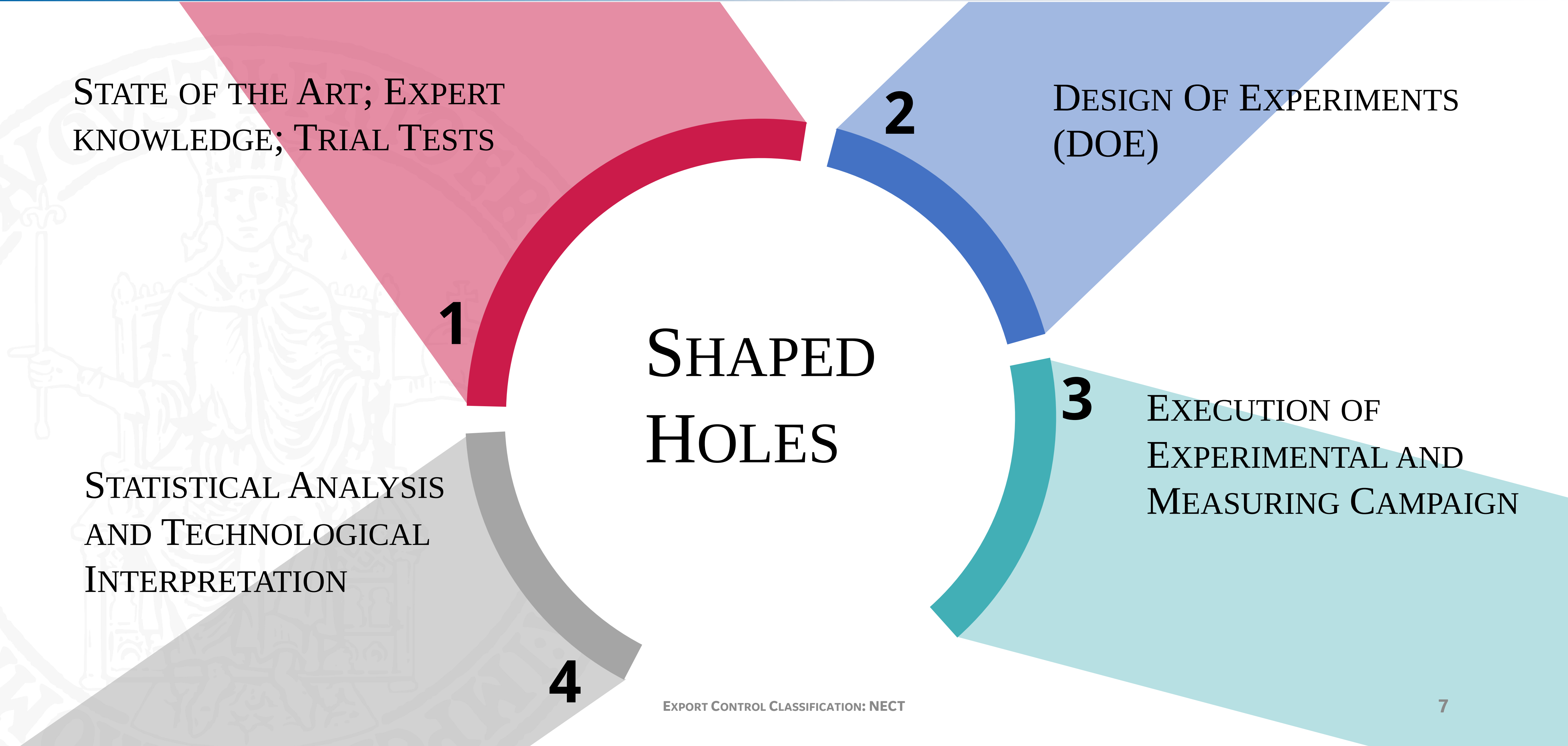
- DIFFUSER: SECTION OF THE HOLE THAT CONTAINS THE DIVERGENT SHAPE. IT IS ON THE EXIT SIDE OF THE AIR PATH AND IT IS USED TO SPREAD, OR DIFFUSE, A FILM OF AIR OVER THE COMBUSTION CHAMBER WALLS



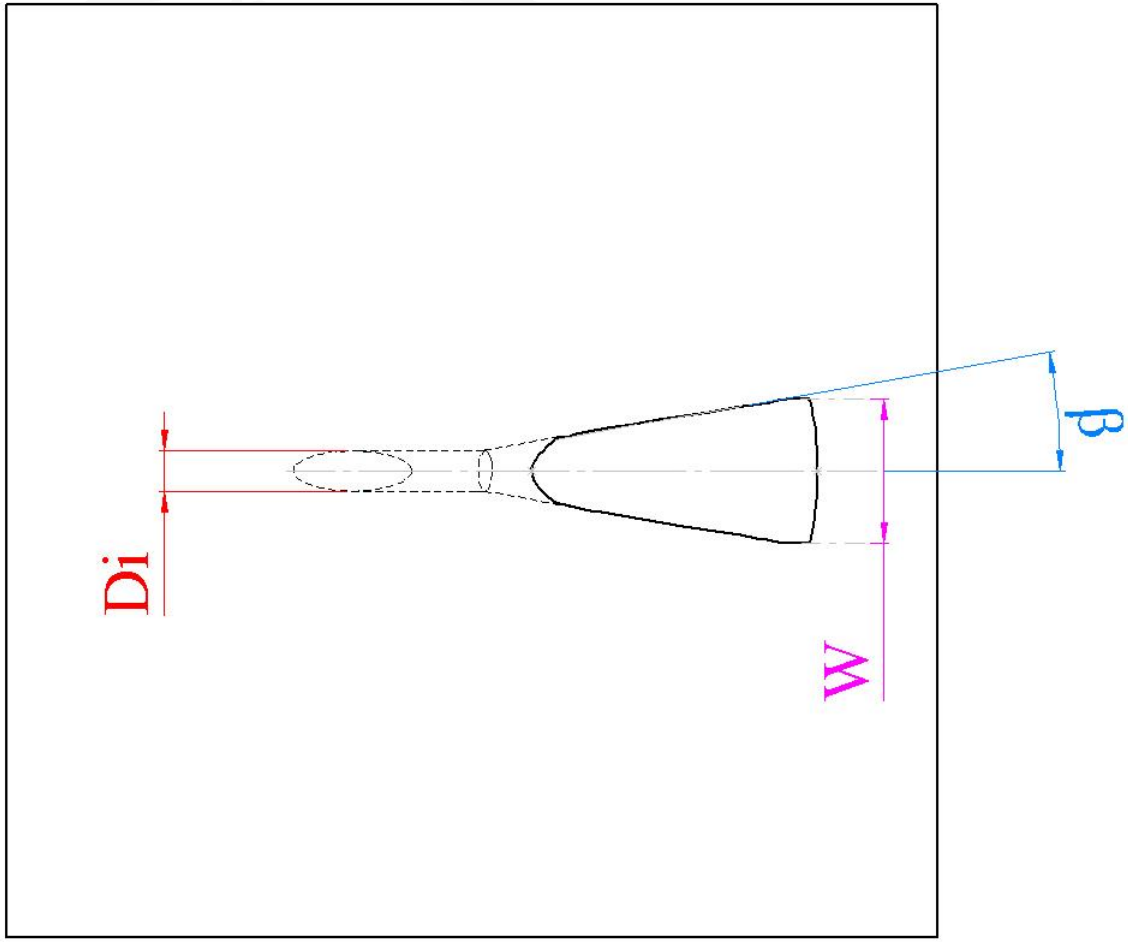
AIMS

THE AIMS OF THIS THESIS ARE :

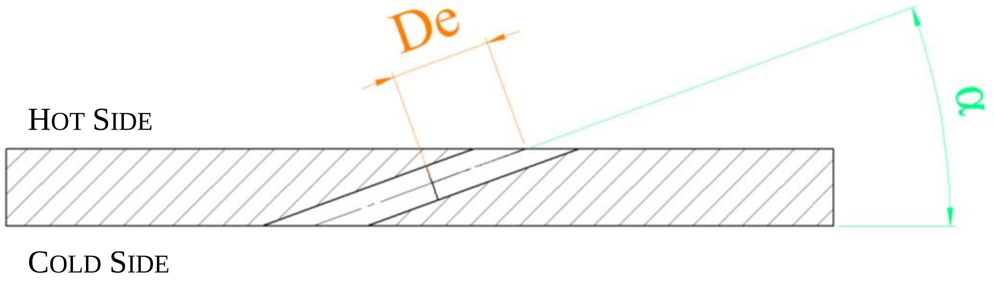
- DEVELOP AND ASSESS **PROCEDURES** AND **METHODS** TO PRODUCE SHAPED HOLES WITH AN ASSIGNED GEOMETRICAL AND METALLURGICAL REQUIREMENTS, BY INVESTIGATING THE **EFFECTS OF DRILLING PROCESS PARAMETERS**
- MINIMIZE THE **WORKING TIME**
- DESIGN A TEST-CASE TO PRODUCE SHAPED HOLES ON **AXIAL-SYMMETRICAL COMPONENTS** BY DRILLING ON FLY (DOF) TECHNIQUE
- INVESTIGATING THE POSSIBILITY TO PRODUCE THE SAME SHAPED HOLES BY **DRILLING FROM THE OPPOSITE SIDE**


State of the Art; Expert knowledge; Trial Tests
1
2
Design Of Experiments (DOE)
Shaped Holes
3
Execution of Experimental and Measuring Campaign
Statistical Analysis and Technological Interpretation
4

SHAPED HOLE CONFIGURATIONS



JOB2



SH CHARACTERISTIC PARAMETERS:

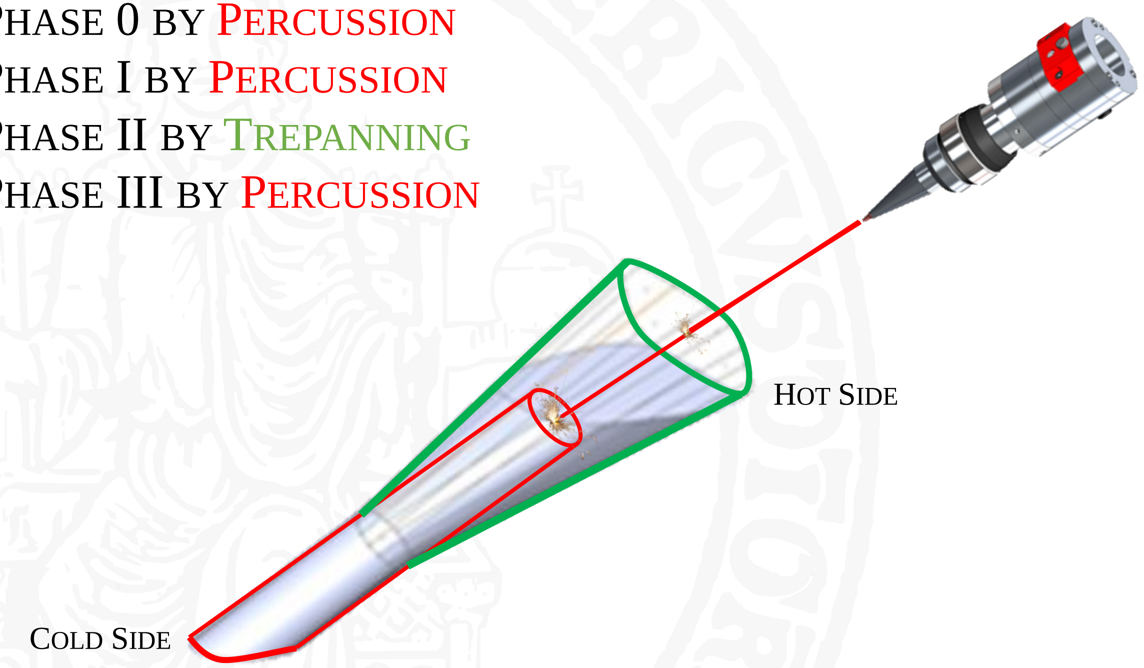
- METERING SECTION AXIS SLOPE – α
- METERING SECTION DIAMETER – Di
- DIFFUSER WIDTH – W
- DIFFUSER ANGLE – β
- DIFFUSER DEPTH – De

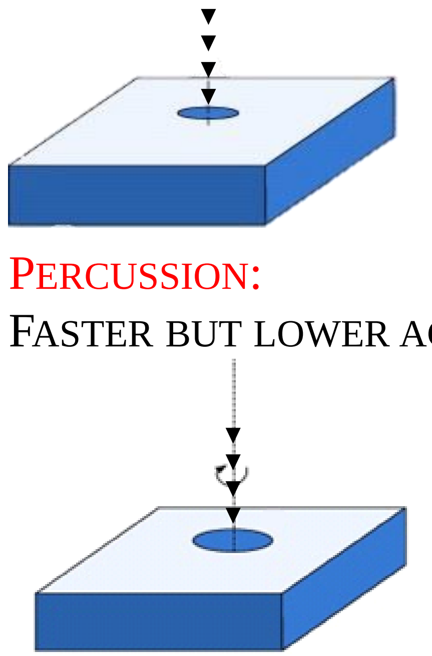
*NUMERICAL VALUES HAVE BEEN HIDDEN

Different drilling methods can be used to produce shaped holes.

To optimize the shaped hole quality while minimizing the production time per single hole it was decided to perform:

- Phase 0 by Percussion
- Phase I by Percussion
- Phase II by Trepanning
- Phase III by Percussion





Percussion:
Faster but lower accuracy

Trepanning:
Slower but higher accuracy

Experimental Equipment ad Matherial

Laserdyne 811 (1200/12000 LS)

- **Work area**
  X 600 mm – Y 600 mm – Z 600 mm
  BeamDirector®: C 900° – D 300°
- **Axis speed**
  X, Y, Z: 50 m/min
  BeamDirector®: 90 rpm
- **Laser source**
  QCW **1200/12000** W pulsed fiber laser
- ***System 94P Interface***
- ***Special features***
  OFC ⟶ Optical Focus Control
  PSC ⟶ Part Surface Control
- ***Assist Gas***
  Inert, reactive

Material: Haynes 188 TBC Coated

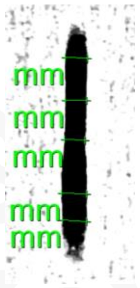
	C	Mn	Si	Cr	Ni	W	La	B	Fe	Co
MIN [%]	0,05	—	0,20	20,0	20,0	13.0	0,02	—	—	Bal
MAX [%]	0,15	1.25	0,50	24.0	24.0	16.0	0,12	0,015	3.0	Bal

Yeld Strength [MPa]	**Tensile Strength [MPa]**	**Elongation at break [%]**
446	963	55

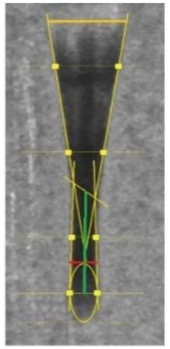
Images Courtesy of Prima Power

MEASURING INSTRUMENTS

X-RAY ANALYSIS

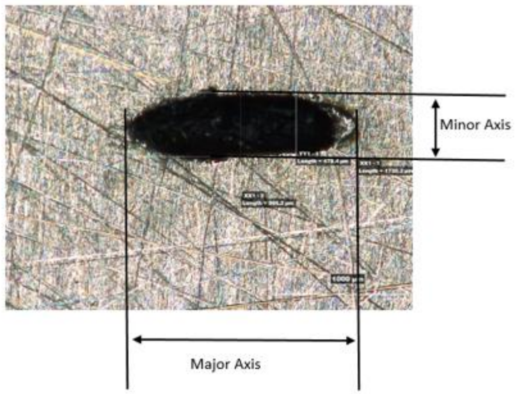


CYLINDRICAL HOLE

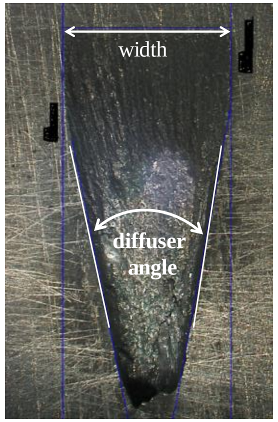


SHAPED HOLE

DIGITAL MICROSCOPE

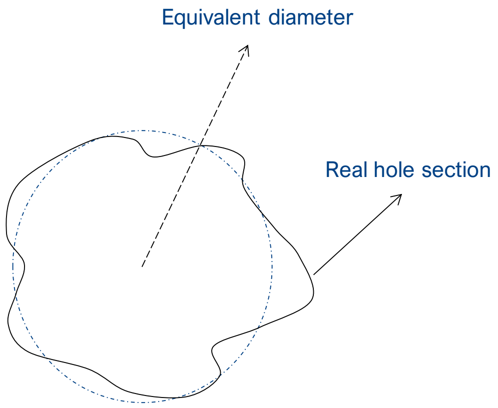


CYLINDRICAL HOLE

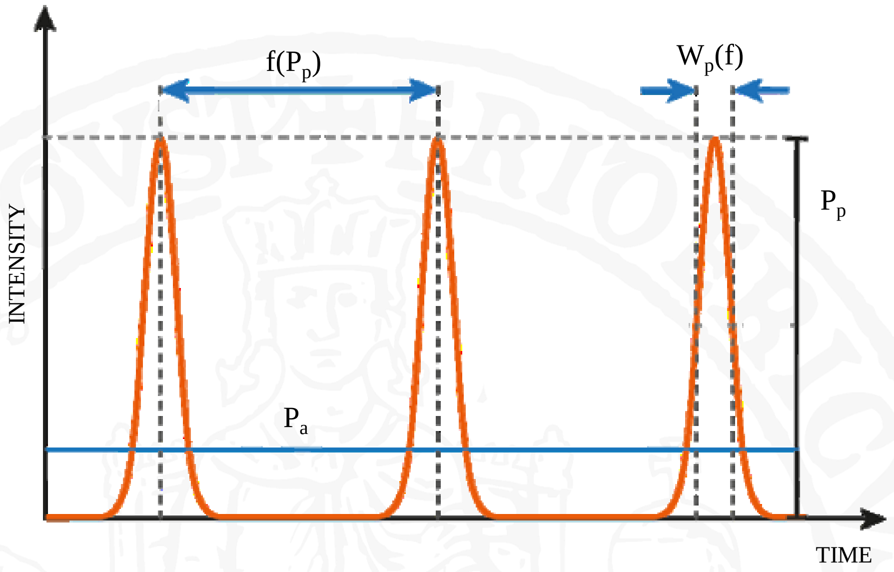


SHAPED HOLE

PNEUMATIC GAUGE



EXPERIMENTAL ACTIVITY

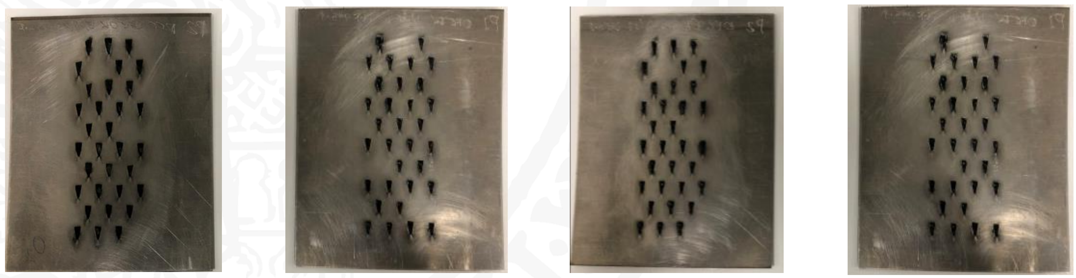


$$P_a = P_p \cdot f(P_p) \cdot w_p(f)$$

FACTORIAL NESTED

EXPERIMENTAL FACTOR	CONTROL/CONSTANT	N° OF LEVELS	LEVELS*
FEEDRATE, R_f	CONTROL	2	-1; 1
PEAK POWER, P_p	CONTROL	2	-1; 1
FREQUENCY, $f(P_p)$	CONTROL	2	-1; 1
PULSE WIDTH, $W_p(f)$	CONTROL	6	-3; -2; -1; 1; 2; 3
ASSIST GAS TYPE, G	CONTROL	2	-1; 1
ASSIST GAS PRESSURE, P_g	CONSTANT	1	k
AVERAGE POWER, P_a	VARIABLE	1	q; p

JOB1: $2^5 \times 4 = 128$ HOLES



JOB2: $2^4 \times 4 = 64$ HOLES

*LEVELS HAVE BEEN CODED

GEOMETRICAL ANALYSIS 1

CORRELATION ANALYSIS 2

METALLOGRAPHIC ANALYSIS 3

GEOMETRICAL ANALYSIS

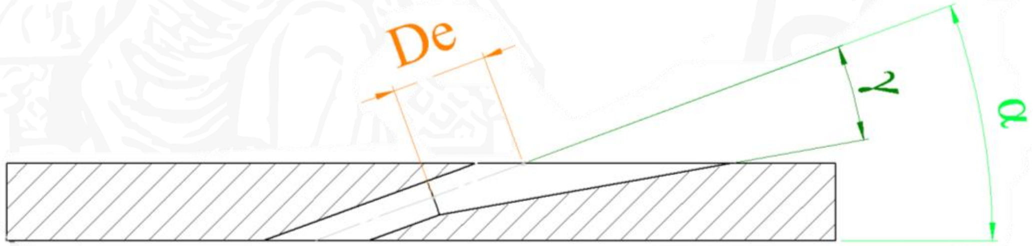
1

- ANOVA
- MAIN EFFECTS PLOTS
- NESTED EFFECTS PLOTS
- INTERACTION PLOTS

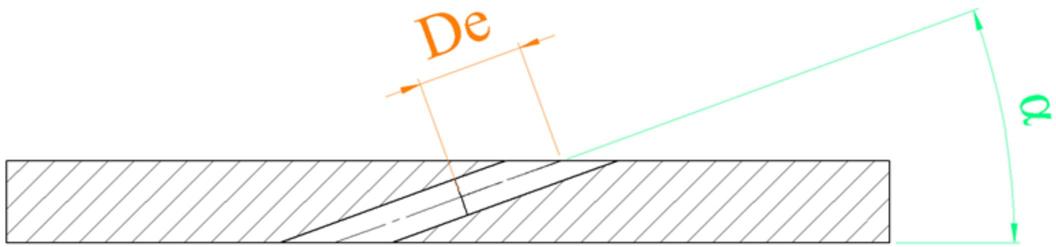
Geometrical Analysis

Response variable	Measuring method	Measuring operators
Metering Section Diameter	Digital microscope	1 (Op.1/Op.2)
	Pneumatic gauge	3 (Op.1; Op.2; Op.3)
	X-Ray	3 (Op.1; Op.2; Op.3)
Diffuser width	Digital microscope	2 (Op.1/Op.2; Op.3)
	X-Ray	3 (Op.1; Op.2; Op.3)
Diffuser angle	Digital microscope	2 (Op.1/Op.2; Op.3)
	X-Ray	3 (Op.1; Op.2; Op.3)
Diffuser depth	X-Ray	2 (Op.1; Op.2)

Job1



Job2

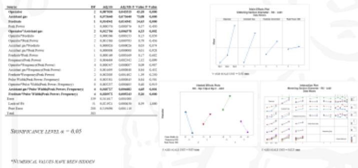


GEOMETRICAL ANALYSIS

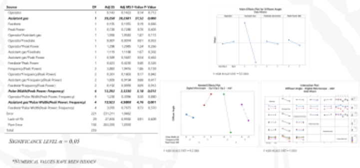
JOB1

JOB2

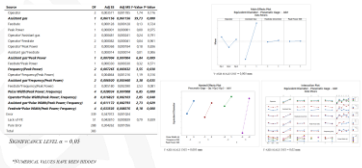
JOB1 – METERING SECTION DIAMETER (X-RAY)



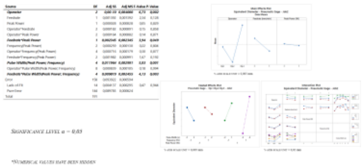
JOB1 – DIFFUSER ANGLE (DIGITAL MICROSCOPE)



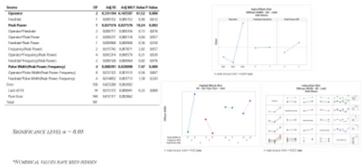
JOB1 – EQUIVALENT DIAMETER (PNEUMATIC GAUGE)



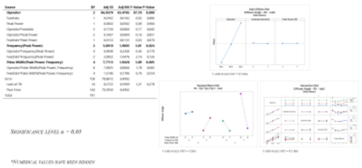
JOB2 – EQUIVALENT DIAMETER (PNEUMATIC GAUGE)



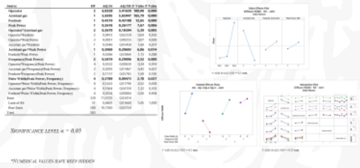
JOB2 – DIFFUSER WIDTH (X-RAY)



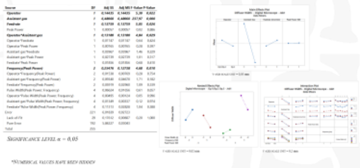
JOB2 – DIFFUSER ANGLE (X-RAY)



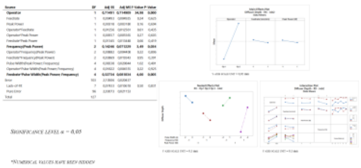
JOB1 – DIFFUSER WIDTH (X-RAY)



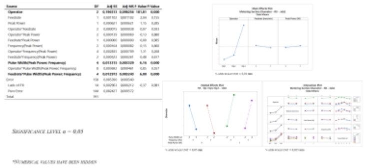
JOB1 – DIFFUSER WIDTH (DIGITAL MICROSCOPE)



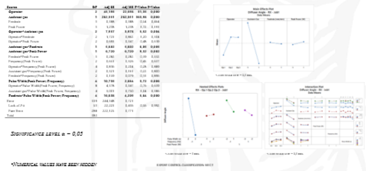
JOB2 – DIFFUSER DEPTH (X-RAY)



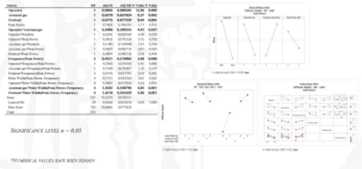
JOB2 – METERING SECTION DIAMETER (X-RAY)



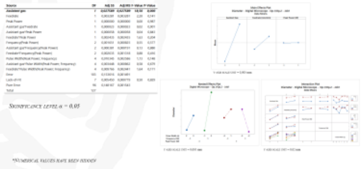
JOB1 – DIFFUSER ANGLE (X-RAY)



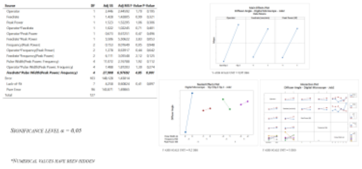
JOB1 – DIFFUSER DEPTH (X-RAY)



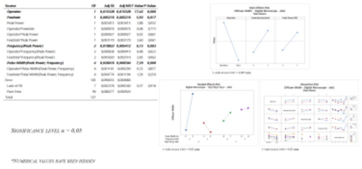
JOB1 – EXIT HOLE DIAMETER (DIGITAL MICROSCOPE)



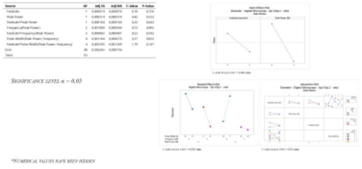
JOB2 – DIFFUSER ANGLE (DIGITAL MICROSCOPE)



JOB2 – DIFFUSER WIDTH (DIGITAL MICROSCOPE)

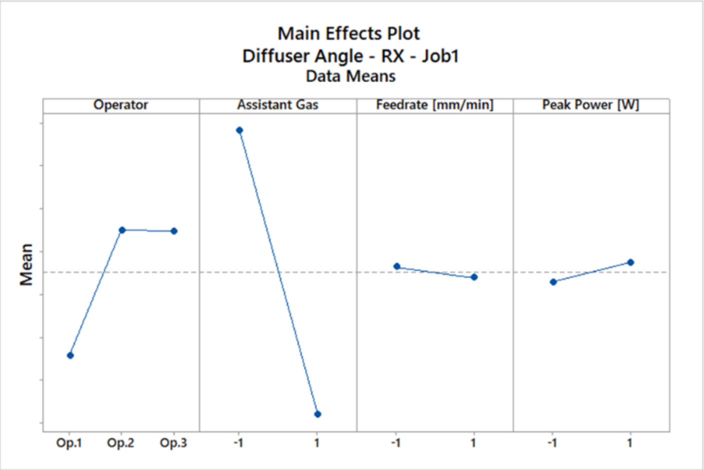


JOB2 – EXIT HOLE DIAMETER (DIGITAL MICROSCOPE)

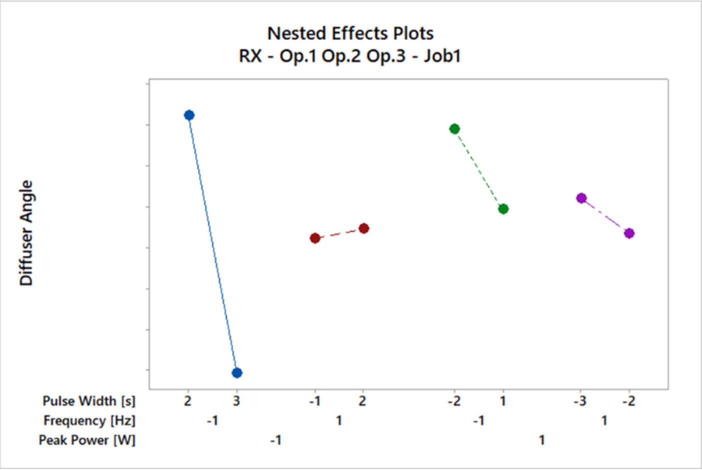


JOB1 – DIFFUSER ANGLE (X-RAY)

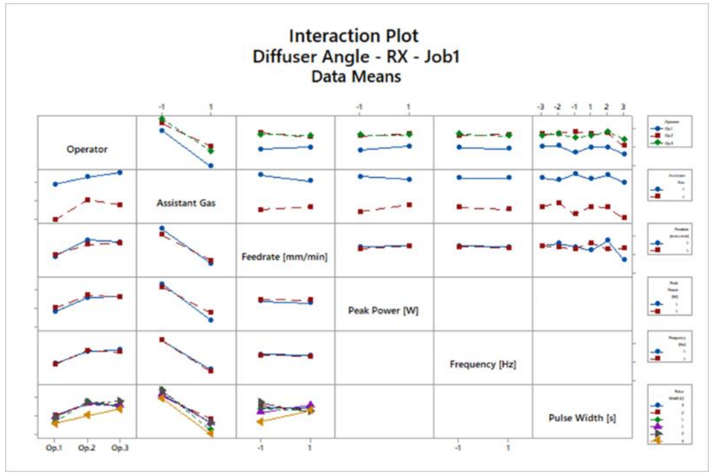
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Operator	**2**	**45,195**	**22,598**	**31,35**	**0,000**
Assistant gas	**1**	**262,351**	**262,351**	**363,98**	**0,000**
Feedrate	1	0,388	0,388	0,54	0,464
Peak Power	1	1,238	1,238	1,72	0,191
Operator*Assistant gas	**2**	**7,957**	**3,978**	**5,52**	**0,004**
Operator*Feedrate	2	1,723	0,862	1,20	0,304
Operator*Peak Power	2	0,693	0,347	0,48	0,619
Assistant gas*Feedrate	**1**	**5,802**	**5,802**	**8,05**	**0,005**
Assistant gas*Peak Power	**1**	**6,720**	**6,720**	**9,32**	**0,002**
Feedrate*Peak Power	1	0,282	0,282	0,39	0,532
Frequency(Peak Power)	2	0,651	0,326	0,45	0,637
Operator*Frequency(Peak Power)	4	0,816	0,204	0,28	0,889
Assistant gas*Frequency(Peak Power)	2	0,321	0,161	0,22	0,800
Feedrate*Frequency(Peak Power)	2	0,159	0,079	0,11	0,896
Pulse Width(Peak Power; Frequency)	**4**	**10,735**	**2,684**	**3,72**	**0,006**
Operator*Pulse Width(Peak Power; Frequency)	8	4,378	0,547	0,76	0,639
Assistant gas*Pulse Width(Peak Power; Frequency)	4	3,001	0,750	1,04	0,386
Feedrate*Pulse Width(Peak Power; Frequency)	**4**	**16,838**	**4,209**	**5,84**	**0,000**
Error	339	244,348	0,721		
Lack-of-Fit	51	22,223	0,436	0,56	0,992
Pure Error	288	222,125	0,771		
Total	383				



Y-AXIS SCALE UNIT = 0,1 DEG



Y-AXIS SCALE UNIT = 1 DEG



Y-AXIS SCALE UNIT = 0,1 DEG

SIGNIFICANCE LEVEL α = 0,05

**NUMERICAL VALUES HAVE BEEN HIDDEN*

JOB1 – DIFFUSER ANGLE (X-RAY)

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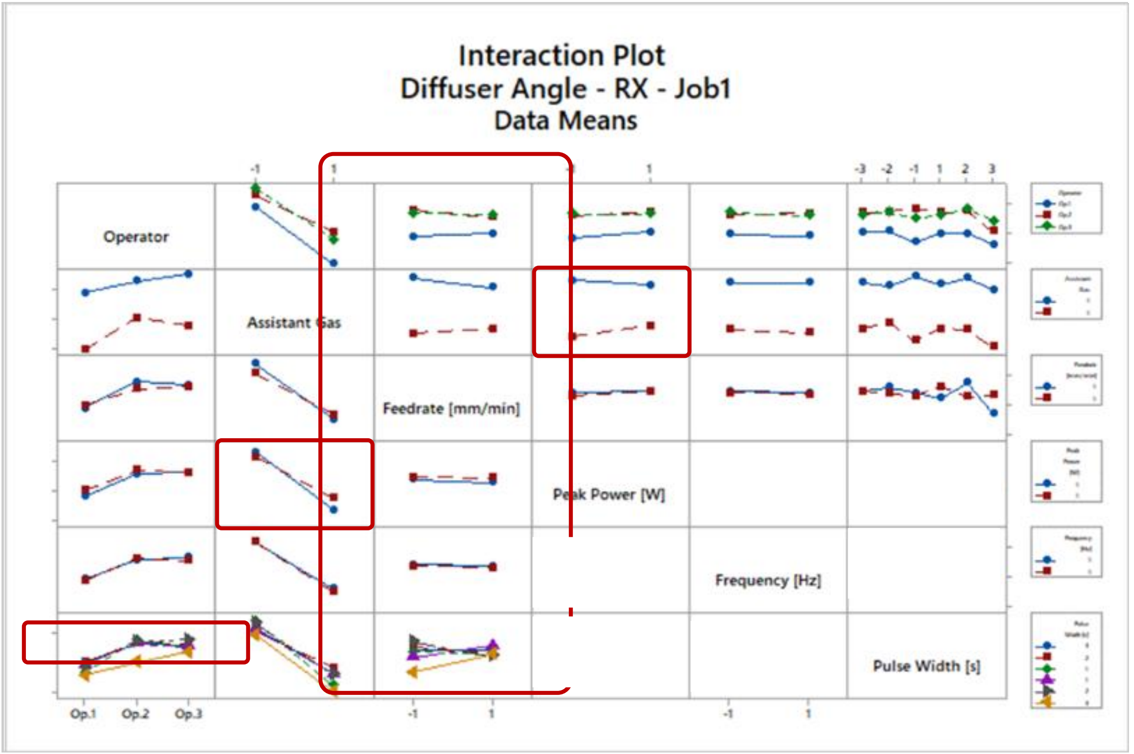


SIGNIFICANCE LEVEL α = 0,05

**NUMERICAL VALUES HAVE BEEN HIDDEN*

EXPERIMENTAL ACTIVITY

GEOMETRICAL ANALYSIS 1

CORRELATION ANALYSIS 2

METALLOGRAPHIC ANALYSIS 3

CORRELATION ANALYSIS 2

VERSUS OPERATORS – FIXED INSTRUMENTS

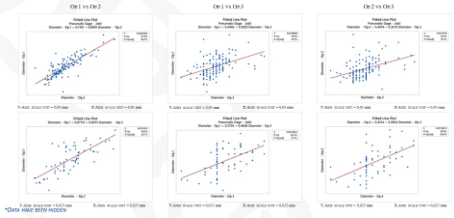
VERSUS INSTRUMENTS – FIXED OPERATORS

Correlation Analysis

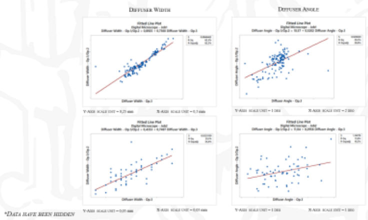
Versus Operators – Fixed Instruments

X-Ray: Metering Section Diameter

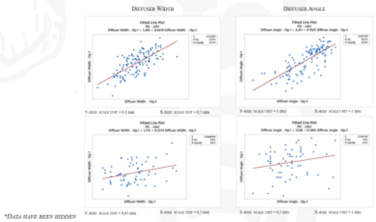
Pneumatic Gauge: Metering Section Diameter



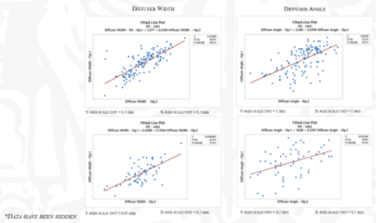
Digital Microscope: Op.1/Op.2 vs. Op.3 → Diffuser Width and Angle



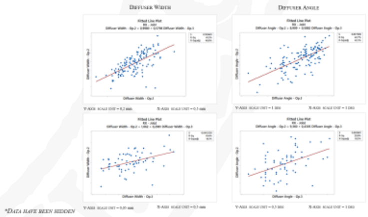
X-Ray: Op.1 vs. Op.3 → Diffuser Width and Angle



X-Ray: Op.1 vs. Op.2 → Diffuser Width and Angle

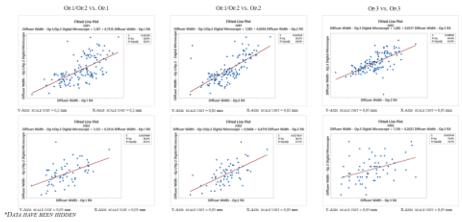


X-Ray: Op.2 vs. Op.3 → Diffuser Width and Angle

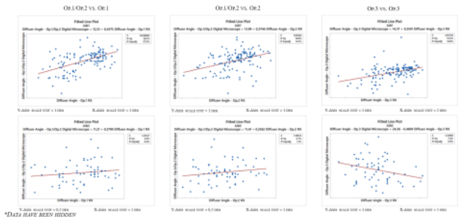


Versus Instruments – Fixed Operators

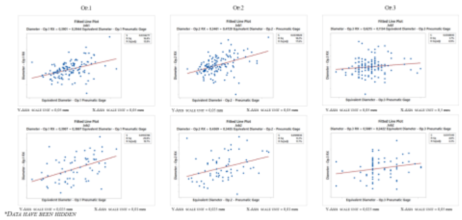
X-Ray vs. Digital Microscope → Diffuser Width



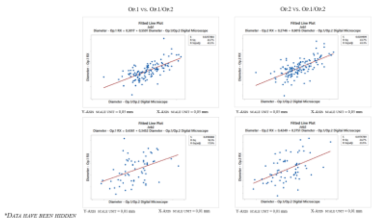
X-ray Vs. Digital Microscope → Diffuser Angle



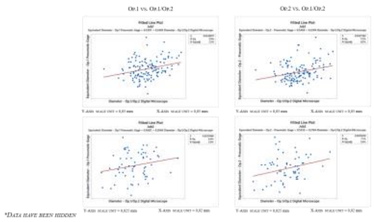
X-Ray vs. Pneumatic Gauge → Hole Diameter



X-Ray Vs. Digital Microscope → Hole Diameter

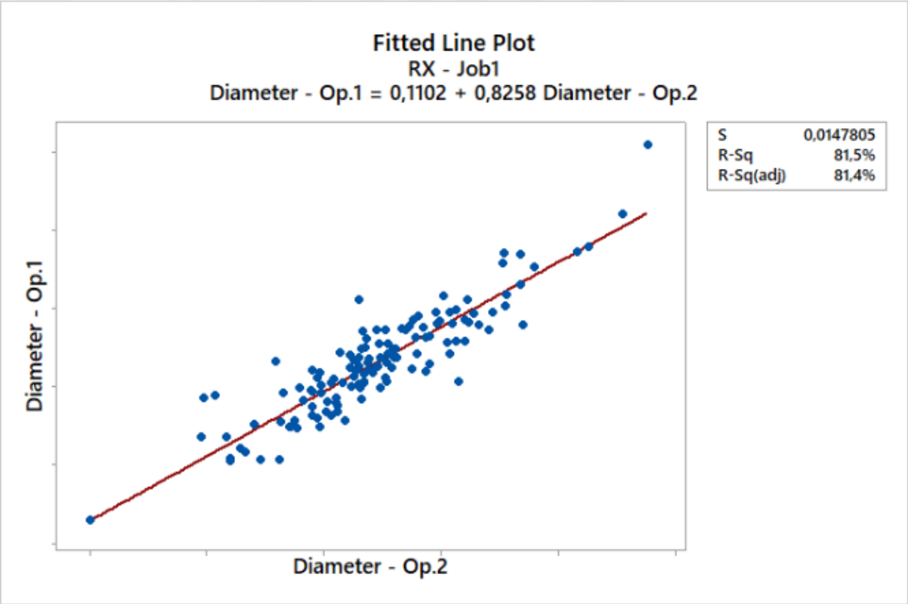


Pneumatic Gauge vs. Digital Microscope → Hole Diameter



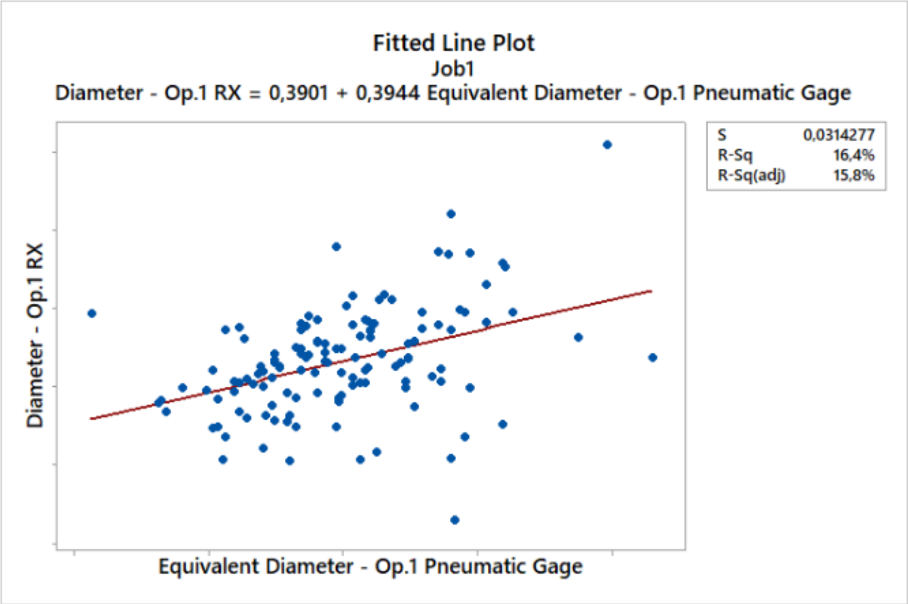
CORRELATION ANALYSIS

VERSUS OPERATORS – FIXED INSTRUMENTS



- *DIFFUSER WIDTH - DIGITAL MICROSCOPE OP.1/OP.2 VS OP.3 FOR JOB1 (R^2= 82.3%)*
- *METERING DIAMETER - X-RAY OP.1 VS OP.2 FOR JOB1 (R^2= 81.5%)*
- *EQUIVALENT DIAMETER - PNEUMATIC GAUGE OP.1 VS OP.2 FOR JOB1 (R^2= 67.0%)*

VERSUS INSTRUMENTS – FIXED OPERATORS



MEASUREMENTS PERFORMED BY THE SAME OPERATOR WITH DIFFERENT INSTRUMENTS NEVER RESULTED CORRELATED (MAX CORRELATION COEFFICIENT WAS ABOUT 45%)

Experimental Activity

Geometrical Analysis 1

Correlation Analysis 2

Metallographic Analysis 3

METALLOGRAPHIC ANALYSIS 3

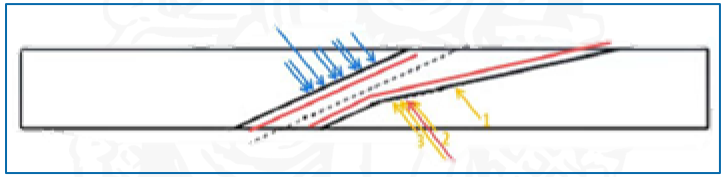
MICROCRACKS
PITTING
RECAST LAYER

Metallographic Analysis

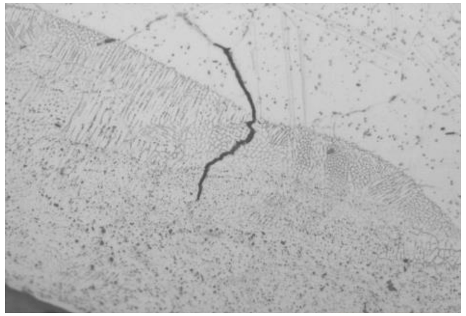
It is crucial to ensure that internal surfaces of the produced holes do not show unacceptable defects in terms of metallurgical quality that may undermine the effectiveness of the coolant flow.

Metallurgical requirements prescribe limits regarding the size of:

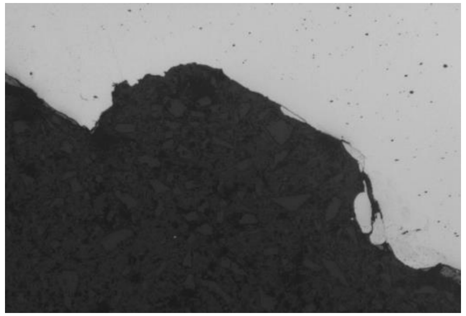
- **Microcrack**
- **Pitting**
- **Recast Layer**



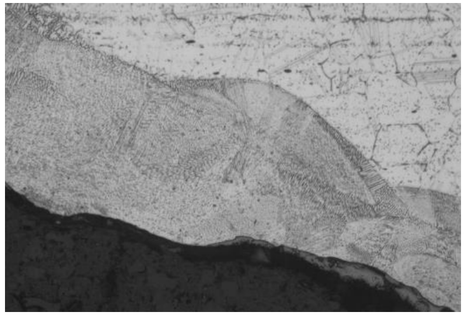
Legenda	
→	Indicative position of other microcracks in the parent metal
→	Position of the microcrack with greater depth in the parent metal (worst condition)
→	Indicative position of others intergranular attacks/oxidations
→	Position of intergranular attack/oxidation with greater depth (worst condition)
→	Indicative position of others pitting
→	Position of pitting with greater depth (worst condition)
—	Zone affected by alloy / carbide depletion
→	Alloy/carbide depletion position with greater thickness
—	Zone affected by recast layer
→	Recast layer position with greater thickness



Microcrack



Pitting



Recast Layer

Metallographic Analysis: Summary Of Results

Job1								Job2			
NON INERT ASSIST GAS				INERT ASSIST GAS				NON INERT ASSIST GAS			
Treatment	Microcracks	Pitting	Recast Layer	Treatment	Microcracks	Pitting	Recast Layer	Treatment	Microcracks	Pitting	Recast Layer
I	2	2	0	XVII	0	1	2	I	1	3	1
II	5	7	1	XVIII	1	12	6	II	0	2	0
III	0	3	0	XIX	0	2	3	III	0	1	0
IV	0	1	0	XX	0	3	6	IV	1	3	0
V	1	0	0	XXI	0	2	1	V	2	2	0
VI	6	2	0	XXII	3	5	2	VI	0	3	0
VII	0	0	0	XXIII	0	5	2	VII	0	0	0
VIII	1	3	1	XXIV	1	7	2	VIII	0	1	0
IX	1	2	1	XXV	0	1	1	IX	0	1	0
X	2	4	1	XXVI	2	8	6	X	0	2	0
XI	0	2	0	XXVII	2	2	3	XI	1	1	0
XII	2	0	1	XXVIII	1	3	6	XII	0	3	0
XIII	0	0	2	XIX	0	3	1	XIII	0	5	0
XIV	2	4	0	XXX	2	6	2	XIV	0	2	0
XV	2	3	0	XXXI	1	3	3	XV	0	2	0
XVI	2	2	0	XXXII	0	7	2	XVI	1	4	1

COMPLIANT → SELECTED AS **BEST TREATMENT**

QUASI-COMPLIANT → FURTHER INVESTIGATION REQUIRED

Best Treatments Replication

Job1

IV	0	1	0
VII	0	0	0
XI	0	2	0
XIII	0	0	2

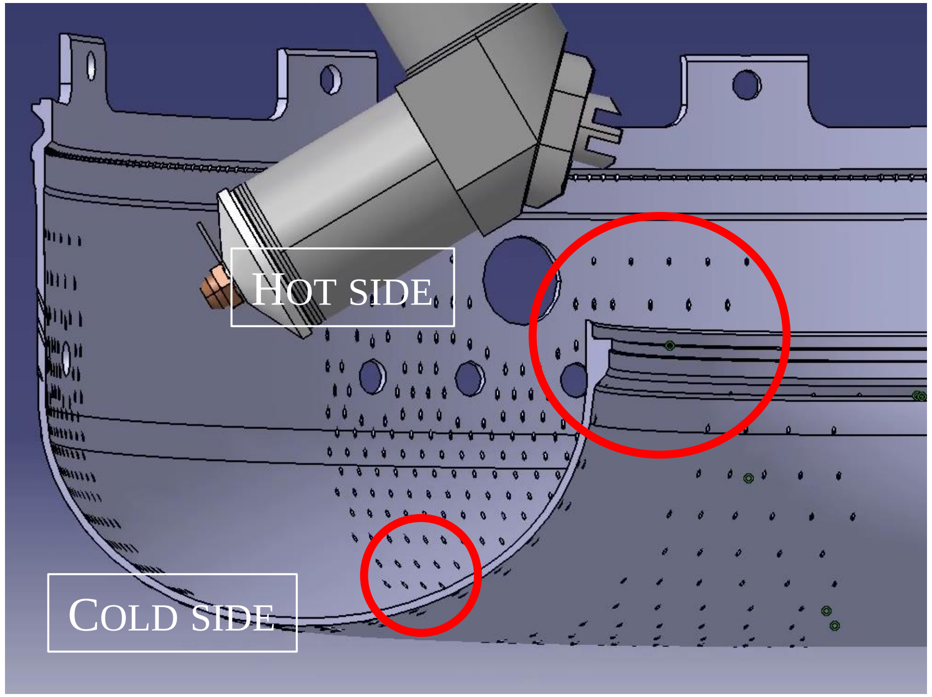
Job2

III	0	1	0
VII	0	0	0

Shaped Holes - Cold Side

Shaped holes manufacturing method currently achieves the holes by laser drilling process *<u>from the hot side to the cold side</u>*.

In particular types of combustors it is impossible to have a complete access for typical laser nozzle to the drilling zone, so it results impossible to produce the shaped holes.



A definitive solution is to drill the hole ***<u>from the cold side to the hot side</u>*** (Shaped Holes - Cold Side).
This would have a significant business impact allowing to develop a new generation of small combustion chambers with inverted flow.

SHAPED HOLES BY COLD SIDE – TRIAL TESTS

A SET OF TRIAL TESTS WAS PERFORMED, BY MODIFYING THE DEFOCUS SETTING AND THE STANDARD PART PROGRAM, RETURNING *PROMISING RESULTS AND CONFIRMING THE POSSIBILITY TO ACHIEVE COMPLIANT SHAPED HOLES FROM THE COLD SIDE*.

PLATE 1

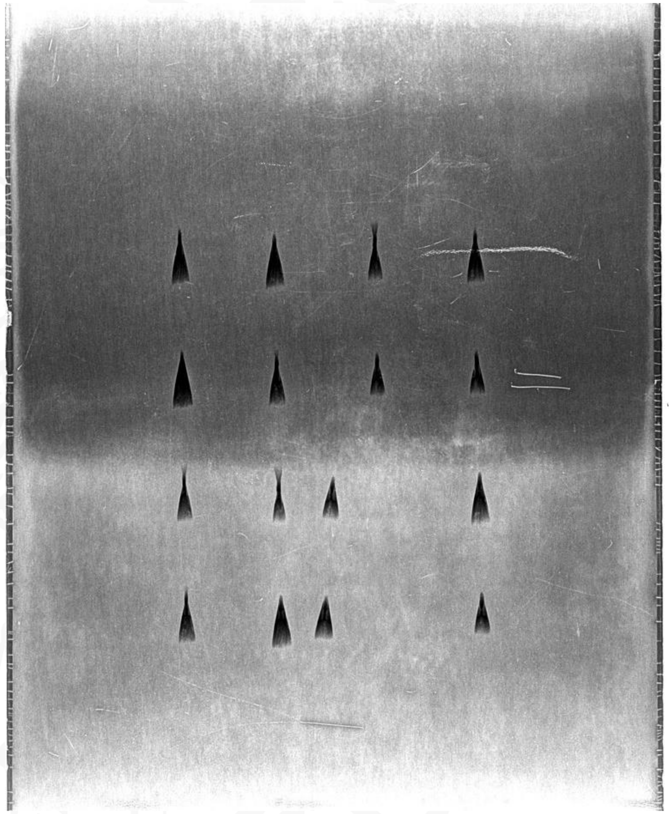
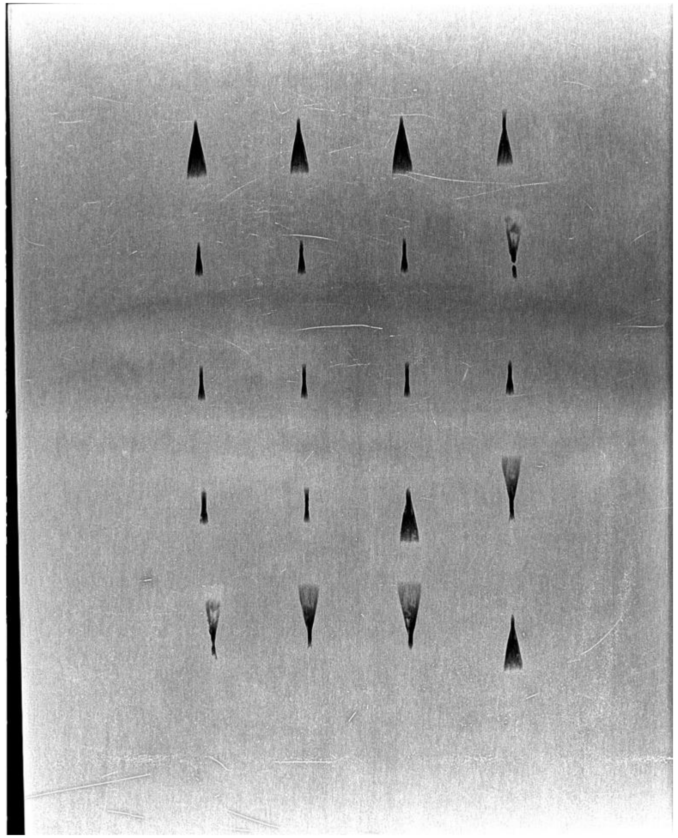
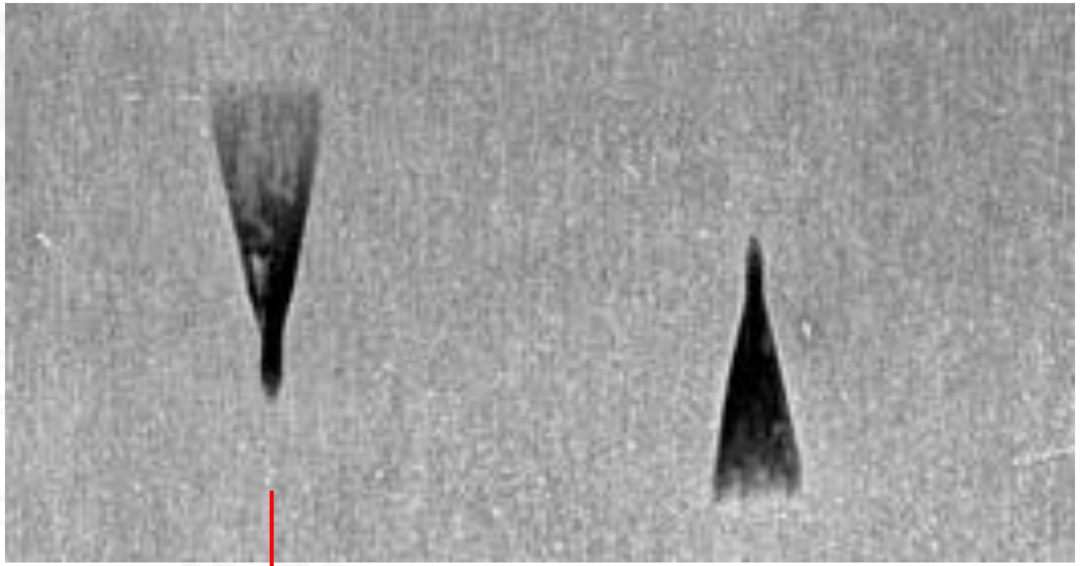


PLATE 2



Shaped Holes by Cold Side – Trial Tests



Classic Shaped Holes

Shaped Holes – Cold Side

Conclusions and Future Developments

Performed Experiments allowed to:

- Evaluate the effects of laser parameters on the achievable geometrical and metallurgical features of Shaped Holes produced
- Evaluate the capability of the available Measuring Instruments/techniques
- Identify and validate the most suitable experimental setup to perform Phase II
- Point out the possibility of tweaking laser parameters to produce Shaped Holes - Cold Side

Future developments should be focused on:

- Bringing off the validation of laser drilling process for the production of Shaped Holes (Confirmatory tests, Flushing Test, Tomography, …)
- Identifying and validating the most suitable experimental setup to perform Phase III
- Investigating the possibility to produce Shaped Holes on axial-symmetrical components by Drilling On Fly (DOF) technique
- Mastering the manufacturing technique for the production of Shaped Holes - Cold Side

THANKS FOR LISTENING